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NEUTRON ACTIVATION IN CASCADE: THE $BeO/LiAlO_2$ CASE*

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Abstract

Neutron activation calculations have been carried out for the Cascade inertial confinement fusion reactor concept. The Cascade chamber [1] features a flowing granular blanket which consists of a carbon surface layer, a BeO multiplier, and a $LiAlO_2$ breeder. The blanket, with an effective thickness of 0.5 m, shields the chamber structural wall, which is made out of silcon carbide. A borated water shield surrounds the chamber. The results of the neutron activation calculations for Cascade indicate that the activity is significantly less than in recent magnetic fusion reactor designs. The activity at shutdown is dominated by ^{24}Na, which is produced by (n,α) reactions with Al. The shutdown decay heat, which is also dominated by ^{24}Na, can be dissipated by thermal radiation so that active shutdown cooling is not required to prevent melting of the blanket materials or chamber structures. In order to qualify for shallow land burial, both the BeO and $LiAlO_2$ will require significant dilution; the BeO is limited by ^{14}C, while $LiAlO_2$ is limited by ^{39}Ar and ^{26}Al.

Neutronics Model

The Cascade chamber is shaped like two cones, with half angles of 35 degrees, attached at their bases (see Ref. 1). For the neutron activation calculations, Cascade was modeled in spherical geometry as illustrated in Fig. 1 and summarized in Table 1. The inner radius of the blanket in the neutronics model is 3.34 m. This is equal to the average distance from the target to the inner surface of the blanket in the conical geometry. The model gives volumes for the various regions within the blanket that are within 10% of the actual volumes in the conical geometry.

A 14.1 MeV neutron source is uniformly distributed in a spherical region of compressed DT which has a density-radius product of 3 g/cm². The inner surface layer of the blanket is represented by a 1-cm-thick region of C with an inner radius of 3.34 m and a packing fraction of 50% . The BeO multiplier is a 10-cm-thick region (3.35 to 3.45 m) at 40% of the normal material density. The 90-cm-thick $LiAlO_2$ breeder extends from 3.45 to 4.35 m and is at 50% normal density. Thus, the total thickness of the blanket is ~ 1 m, while the effective material thickness is ~ 0.5 m due to the porous nature of the flowing granule material. A 2-cm-thick SiC chamber wall surrounds the blanket extending from 4.35 to 4.37 m.

The entire chamber is surrounded by a borated-water, radiation shield. The inner radius of the shield is 7.48 m. It consists of a 2-cm-thick Al liner, a 1-m-thick water region, and a 1-m-thick borated water region. Both water regions contain 10 vol% Al as the structural material. Boron is excluded from the inner half of the shield in order to make it a more effective neutron reflector for the chamber.

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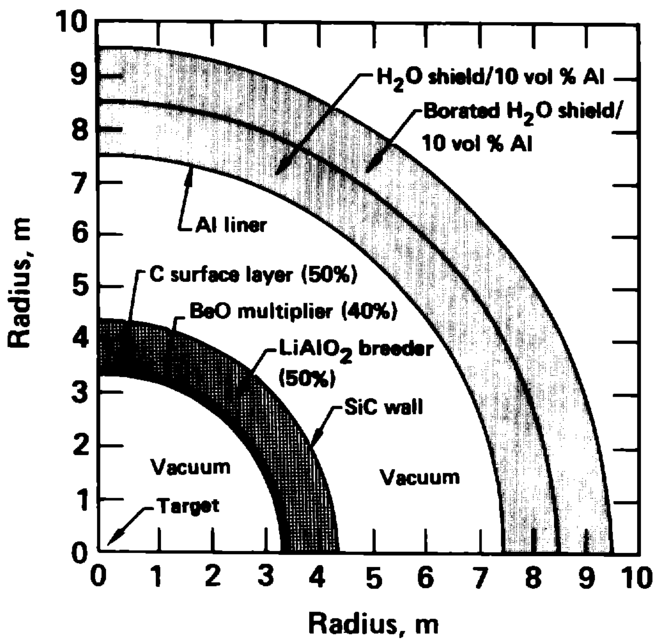

Fig. 1 Illustration of the neutronics model for the Cascade reactor.

Table 1. Neutronics Model for the Cascade Chamber.

Region	Material	Inner radius (m)	Outer radius (m)	Density (g/cc)
Surface	C	3.34	3.35	0.850
Multiplier	BeO	3.35	3.45	1.204
Breeder	$LiAlO_2$	3.45	4.35	1.275
Wall	SiC	4.35	4.37	3.200
Liner	Al	7.48	7.50	2.700
Shield	H_2O-Al	7.50	8.50	1.170
Shield	H_2O-Al-B	8.50	9.50	1.170

Material Composition

The compositions of the materials used in the activation calculations are listed in Table 2. The impurity levels in the carbon surface layer are based on those listed for a high purity graphite in Ref. 2. We assumed that the impurities in the BeO are mainly carried over by the Be metal. The impurity elements in Be and their levels were taken from the Blanket Comparison and Selection Study (BCSS) Final Report [3]. The $LiAlO_2$ composition was also taken from the BCSS. The SiC composition is an approximation based on the composition reported in Ref. 4, which shows all impurity levels (except Fe) being well below 1 weight-part-per-million (wppm); we have conserva-

Table 2. Composition of Materials used in Cascade (wt%).

Element	C	BeO	$LiAlO_2$	SiC	Al	Shield
Hydrogen	---	---	---	---	---	8.6076
Lithium	---	0.0001	10.4842	---	---	---
Beryllium	---	35.9313	0.0010	---	---	---
Boron	0.0002	0.0001	0.0010	---	---	---
Carbon	99.9760	0.0360	---	29.9547	---	---
Nitrogen	---	0.0108	---	---	---	---
Oxygen	---	63.8778	48.3423	---	---	68.3155
Sodium	0.0019	---	0.0050	0.0001	---	---
Magnesium	---	0.0288	---	---	0.7000	0.1615
Aluminum	---	0.0324	40.7585	---	98.0500	22.6267
Silcon	---	0.0216	---	---	0.4000	0.0924
Phosphorous	---	---	0.0500	---	---	---
Sulfur	0.0003	---	---	---	---	---
Chlorine	---	---	0.0100	---	---	---
Potasssium	---	---	0.0500	---	---	---
Calcium	0.0073	0.0072	0.0030	---	---	---
Scandium	---	---	---	0.0001	---	---
Titanium	0.0004	---	0.0030	---	0.1000	0.0231
Vanadium	0.0004	---	0.0030	---	---	---
Chromium	---	0.0036	0.0030	---	0.1000	0.0231
Manganese	---	0.0054	0.0010	0.0001	0.1000	0.0231
Iron	0.0014	0.0216	0.0030	0.0011	0.3500	0.0808
Cobalt	---	0.0002	0.0030	0.0001	---	---
Nickel	---	0.0108	0.0020	---	---	---
Copper	---	0.0036	0.0010	---	0.1000	0.0231
Zinc	---	0.0072	0.0500	---	---	---
Arsenic	---	---	0.0500	0.0001	0.1000	0.0231
Strontium	---	---	0.1000	---	---	---
Zirconium	---	---	0.0100	---	---	---
Molybdenum	---	0.0007	0.0030	---	---	---
Silver	---	---	0.0010	---	---	---
Cadmium	---	0.0001	0.0100	---	---	---
Tin	---	---	0.0300	---	---	---
Antimony	---	---	0.0100	---	---	---
Barium	---	---	0.0100	---	---	---
Tungsten	---	---	---	0.0001	---	---
Lead	0.0121	0.0007	0.0010	---	---	---
Bismuth	---	---	0.0010	---	---	---

tively set them equal to 1 wppm. The impurity elements and their levels in the Al liner were also taken from Ref. 4. The composition of the shield is 10 vol% Al and 90 vol% water. The impurities are assumed to be entirely due to the Al structure.

Neutron Spectra and Flux Levels

The resulting neutron spectra in the blanket zones and the chamber wall are shown in Fig. 2. The neutronics calculation required to determine these spectra was carried out with TART, a 175 energy group, Monte Carlo, neutron transport code [5]. The spectra and flux in the C surface layer and BeO multiplier are quite similar, therefore, only the BeO spectrum is shown. It has the characteristic 14 MeV peak and a tail of lower energy neutrons which have been moderated in the compressed DT target and / or the blanket itself. The spectrum in the $LiAlO_2$ breeder region has an order of magnitude lower 14 MeV peak. Also note that the low energy neutrons are very effectively absorbed by lithium in tritium breeding reactions. The spectrum in the SiC chamber wall shows that the 14 MeV component has been reduced by over two orders of magnitude compared to the inner surface of the blanket.

The total neutron flux in each region is listed in Table 3. Only the inner half of the shield is shown. Out of 20,000 neutron histories in the Monte Carlo calculation, no neutrons entered the outer half of the shield. This is consistent with GA's findings [6] that showed that a 1-m-thick shield reduces the flux by four orders of magnitude. The first column is the flux in the chamber or shield zone at full power. It is based on a fusion power of 1500 MW which is equivalent to a 14.1 MeV source of 5.33 E+20 neutrons per second. The three granular materials, however, circulate in and out of the chamber as they go through heat exchangers. Therefore, in the activation calculations, the fluxes were reduced by the ratio of the time the material is in the chamber to the total circulation time. This is equal to the ratio of the blanket zone inventory to the total inventory for each of the three circulating blanket materials. These ratios are:

C	1.2 Mg /	52.6 Mg	= 0.023
BeO	17.5 Mg /	54.0 Mg	= 0.324
$LiAlO_2$	220.0 Mg /	390.0 Mg	= 0.564

The full power flux was also reduce by a factor of 0.7 for all the regions to account for an assumed plant capacity factor of 70% . The adjusted average flux levels are given in the second column of Table 3. Note that these fluxes were then applied to the entire inventory when calculating the activation levels.

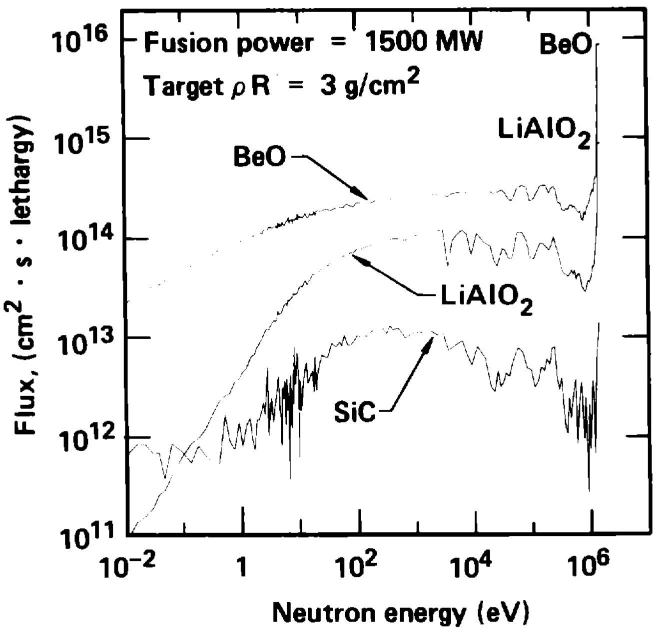

Fig. 2 Neutron spectra in the various regions of the chamber.

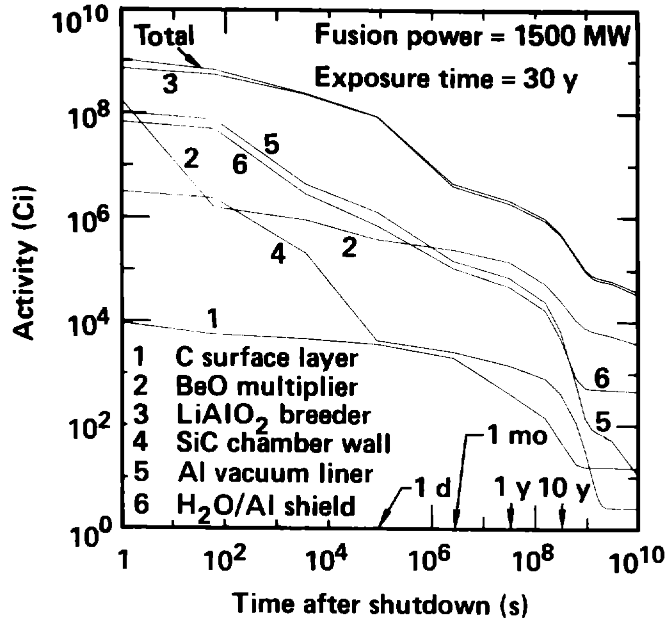

Fig. 3 Activity as a function of time after shutdown.

Table 3. Flux levels in Chamber and Shield (n/cm²s).

Region	Full Power	Average
C surface layer	4.10 E+15	6.55 E+13
BeO multiplier	3.72 E+15	8.44 E+14
$LiAlO_2$ breeder	9.81 E+14	3.87 E+14
SiC wall	1.08 E+14	7.57 E+13
Al liner	6.10 E+13	4.27 E+13
H_2O shield	4.12 E+12	2.88 E+12

Activation

One-group, neutron activation cross sections were calculated for each region using the ORLIB code [7] which makes use of the energy dependent fluxes from TART and the ACTL cross section library [8]. The resulting activation cross sections were then used in the FORIG code [9] to determine the time-dependent activity, afterheat, biological hazard potential, and shallow burial index for each region. The irradiation time was taken as the assumed 30 year life of the plant.

Activity

The activity (by region and the total) as a function of time after shutdown is shown in Fig. 3. The total activity 1 second after shutdown is 1 GCi. It falls by an order of magnitude during the first day and by a factor of 200 during the first month after shutdown. Thirty years after shutdown the activity is down by four orders of magnitude to 0.1 MCi.

As seen in Fig. 3, the activity is strongly dominated by the activity in the $LiAlO_2$ breeder region. For the first day, ^{24}Na, which is produce by (n,α) reactions with ^{27}Al, dominates the activity. ^{24}Na beta decays with a half-life of 15 hours and emits two hard gammas with energies of 2.75 and 1.37 MeV. From several days to about 20 years, ^{60}Co is the primary contributor to the activity in the $LiAlO_2$. It is produced by neutron capture in the ^{59}Co impurities. ^{60}Co beta decays with a half-life of 5.3 years and emits two gammas of 1.17 and 1.33 MeV. Beyond 20 years the activity in the $LiAlO_2$ is dominated by ^{39}Ar, which is primarily produced by (n,p) reactions with ^{39}K impurities. ^{39}Ar beta decays with a half-life of 269 years and does not emit any gammas.

Table 4. Comparison of activity in Cascade, Mars and Starfire (Ci/W_e relative to Cascade).

	Time after shutdown		
	0	1 y	100 y
Cascade	1.0	1.0	1.0
Mars	4.8	280	1.2
Starfire	3.5	190	3.1

The activity levels in Cascade are significantly less than in other recent fusion reactor studies. In Table 4 the activities in the Mars [10] and Starfire [11] magnetic fusion reactor designs are compared to Cascade. The comparison is made on a Curie per unit net electric power basis; the net electric power of Cascade is 815 MW_e, while Mars and Starfire both have net powers of 1200 MW_e. The activity in Cascade is lower by a factor 3.5-4.8 at shutdown, a factor of 190-280 one year after shutdown, and a factor of 1.2-3.1 at 100 years after shutdown. These results do not include the activity of first walls or blanket materials that may require replacement during the life of the power plants.

The activities at selected times after shutdown for the various regions are listed in Table 5. The dominant contributor is also listed.

Neutronics and activation calculations for an earlier version of the Cascade chamber, which used a Li_2O breeder, were reported Blink [12]. His results give an activity at shutdown with the Li_2O breeder that is about an order of magnitude less than those reported here for the $LiAlO_2$ case.

Table 5. Activity at selected times after shutdown (Ci).

Region	Time after shutdown 0	1 d	1 m	1 y	10 y	100 y
C surface layer	4.63 E5 ^{12}B	3.69 E3 ^{37}Ar	2.03 E3 ^{37}Ar	4.19 E2 ^{55}Fe	4.88 E1 ^{55}Fe	1.51 E1 ^{14}C
BeO multiplier	3.08 E8 ^{6}He	3.79 E5 ^{24}Na	2.44 E5 ^{55}Fe	1.43 E5 ^{55}Fe	2.58 E4 ^{60}Co	5.33 E3 ^{14}C
$LiAlO_2$ breeder	7.31 E8 ^{24}Na	8.64 E7 ^{24}Na	4.05 E6 ^{60}Co	1.87 E6 ^{60}Co	4.69 E5 ^{60}Co	5.12 E4 ^{14}C
SiC wall	3.11 E6 ^{28}Al	4.35 E3 ^{60}Co	2.64 E3 ^{60}Co	1.44 E3 ^{60}Co	4.13 E2 ^{60}Co	2.54 E0 ^{14}C
Al liner	1.03 E8 ^{28}Al	1.27 E6 ^{76}As	1.50 E5 ^{55}Fe	7.18 E3 ^{55}Fe	6.67 E3 ^{55}Fe	4.98 E1 ^{63}Ni
H_2O shield	6.76 E7 ^{28}Al	6.98 E5 ^{76}As	1.08 E5 ^{55}Fe	4.82 E4 ^{55}Fe	4.82 E3 ^{55}Fe	4.84 E2 ^{14}C

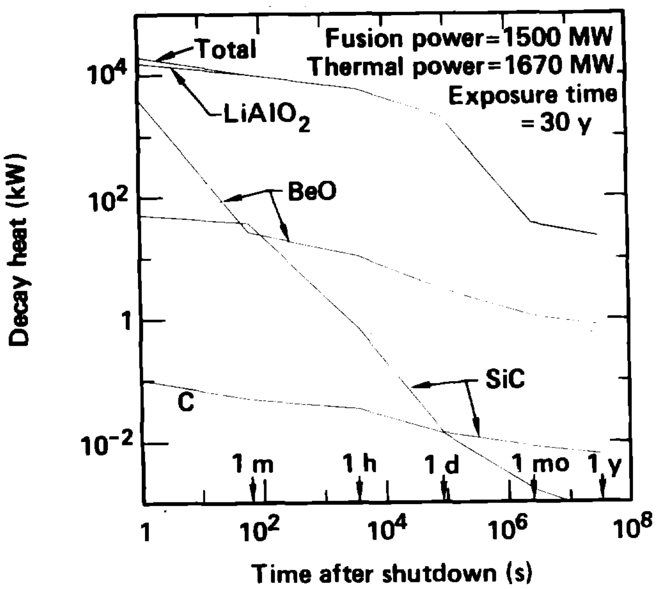

Fig. 4 Decay heat as a function of time after shutdown.

Decay Heat

The radioactive decay heat as a function of time after shutdown is shown in Fig. 4. The decay heat at shutdown is 21.8 MW, and it drops off to 6 MW during the first hour after shutdown. During this period it is dominated by ^{24}Na in the $LiAlO_2$. The SiC chamber, wall, which operates at 1200 K, can radiate ~30 MW to the surrounding water shield, which provides an large thermal sink. Thus we expect that the decay heat can be removed by thermal radiation without the need for active cooling systems. Even with absolutely no heat removal from the $LiAlO_2$, it would take about one week before it would reach its melting point.

Biological Hazard Potential

The inhalation biological hazard potential (bhp) is the volume of air required to dilute vaporized material to breathing standards. Table 6 give the bhp

Table 6. Inhalation biological hazard potential (bhp) (km^3 of air).

Region	Time after shutdown 1 h	1 d
C surface layer	7.8 E+2 (^{22}Na)	6.1 E+2 (^{22}Na)
BeO multiplier	3.0 E+5 (^{60}Co)	2.5 E+5 (^{60}Co)
$LiAlO_2$	5.8 E+7 (^{24}Na)	2.7 E+7 (^{24}Na)
SiC wall	1.7 E+4 (^{31}Si)	6.9 E+3 (^{60}Co)
Al liner	6.6 E+5 (^{76}As)	2.9 E+5 (^{76}As)
H_2O shield	3.4 E+5 (^{76}As)	1.4 E+5 (^{76}As)
TOTAL	5.9 E+7	2.8 E+7

for the various regions in the Cascade chamber. If we assume a plume containing vaporized radioactive material that is tens of km^3, then the allowable release fraction can be determined from Table 6. At one day after shutdown a release fraction of ~ 10^{-4} of the BeO would be tolerable while the release of $LiAlO_2$ would have to limited to ~ 10^{-6}. These fractions are somewhat more restrictive than the Li_2O version of Cascade [12]. The probability of release is expected to be low due to the use of high temperature materials and the absence of volatile materials within the chamber.

Shallow Burial Index

The shallow burial index (SBI) is the ratio of the specific activity (Ci/m^3) to the legal limit; thus, a value below 1.0 allows legal burial. The activity for each region at 10 y after shutdown was divide by the volume of material corresponding to that region and then divided by the legal limit to give the SBI. The volume used in this calculation was the full-density volume of the total inventory of material. For example, the 390 Mg of $LiAlO_2$ has a full-density volume of (3.9E8 g)/(2.55 g/cm^3) = 153 m^3.

The results for each region are given in Table 7. The first column is based on guidelines given in 10CFR61 [13]. There are, however, several long-lived isotopes produced in fusion reactors that are not currently limited. Maninger and Dorn have estimated limits for some of these isotopes [4]. The resulting SBI based on the full set of limits is given in column 2 of Table 7. Note that References 4 and 11 do not give a limit for ^{39}Ar. Since ^{39}Ar and ^{14}C both

Table 7. Shallow burial index (SBI) for Cascade.

Region	SBI based on limits given in: 10CFR61	Ref. 4
C surface layer	0.07 (^{14}C)	0.07 (^{14}C)
BeO multiplier	23.61 (^{14}C)	23.96 (^{14}C)
$LiAlO_2$ breeder	3.23 (^{14}C)	90.64 (^{39}Ar)[a]
SiC wall	0.06 (^{14}C)	0.06 (^{14}C)
Al liner	0.01 (^{63}Ni)	0.73 (^{26}Al)
H_2O shield	0.07 (^{14}C)	0.07 (^{14}C)

a) Assumes 8 Ci/m³ limit for ^{39}Ar (same as for ^{14}C) as suggested in Ref 6.

beta decay without emitting any gammas, Chen [6] suggested that the limit for ^{39}Ar be set equal to that for ^{14}C. The limit for ^{14}C is 8 Ci/m³ if it is not in a metal and 80 Ci/m³ if it is in a metal. The 8 Ci/m³ limit is used in column 2.

As indicated, the BeO exceeds the limit by a factor of nearly 24, virtually entirely due to the ^{14}C. About 60% of the ^{14}C is produced by (n,α) reactions with ^{17}O, while the remainder is produced by (n,p) reactions with ^{14}N impurities. The SBI of 90.6 for $LiAlO_2$ is dominated by the ^{39}Ar (51.8) and ^{26}Al (32.7). ^{39}Ar is produced by (n,p) reactions with ^{39}K impurities while ^{26}Al is produced from (n,2n) reactions with ^{27}Al. Reducing the K impurity level in the $LiAlO_2$ and using a thicker BeO region would help to reduce the SBI for the $LiAlO_2$. Even so, it appears that significant dilution will be required in order for the BeO and $LiAlO_2$ to qualify for shallow land burial. All other materials qualify for shallow burial without dilution.

Summary

Neutron activation calculations have been carried out for the Cascade reference design. The total activity in the Cascade reactor at shutdown is a factor of 3.5 - 4.8 less than in the magnetic fusion reactor designs, Starfire and Mars, respectively. ^{24}Na, which is produced from $^{27}Al(n,\alpha)$ reactions in the $LiAlO_2$, dominates the activity, decay heat, and biological hazard potential for the first couple days after shutdown. With this high temperature chamber design, the decay heat can be removed by thermal radiation to the surrounding water shield to prevent melting of blanket and chamber materials. Shallow land burial will be possible only if the BeO and $LiAlO_2$ are diluted by factors of 24 and 91, respectively. ^{14}C is the limiting isotopes in the BeO, while ^{39}Ar and ^{26}Al limit the burial of $LiAlO_2$.

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